THE

GEOLOGICAL MAGAZINE

VOLUME LXII.

No. XII.—DECEMBER, 1925.

ORIGINAL ARTICLES.

Radioactivity and the Earth's Thermal History. Part V: The Control of Geological History by Radioactivity.

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(*Concluded from p. 515.*)

Structure of the Lithosphere.
The Granitic Layer of the Continents.
The Basaltic Layer.
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The Peridotite Zone.
The Relation to Geological Time.

The Structure of the Lithosphere.

In Part IV of this paper the theory that the earth has continuously cooled down from a former molten state was shown to lead to limitations of temperature and to a distribution of rock-types at moderate depths which, taken together, made it impossible for igneous activity to have taken place as we know it to have done. It was argued that this conclusion definitely proved the theory to be wrong. Now, instead of deducing the distribution of rock-types in depth from their radioactive contents, the method of attack will be reversed and an attempt will be made to determine the downward distribution independently, so that the radioactive effects may be deduced without reference to any limiting hypothesis of a steadily cooling earth.

Washington has paved the way by a recent paper in which he presents evidence to prove that "the average density of the rocks of a region varies in the opposite sense as the average altitude".[1] The higher regions of the earth approach a lower limit of density of 2·60, and the deeper sub-oceanic regions 3·25; the figure for continental regions of average height being 2·79. Washington then goes further and calculates the level of compensation, or as he prefers to call it, the "isopiestic level", from the average altitudes and densities of a large number of areas. By the method of least squares the most probable value is found to be 59 km. below sea-level, a figure that is surprisingly close to Bowie's value of 60 km. based on gravity observations at stations widely distributed over

[1] *Bull. Geol. Soc. Am.*, vol. xxxiii, 1922, p. 375.

the United States. In itself this remarkable and almost accidental correspondence does not necessarily mean that each figure obtained from an area of surface rocks applies to the whole column beneath, but it does definitely mean that the actual differences between the average densities of high-standing and low-standing columns have been closely arrived at. Thus, if 2·60 is thought to be too low for Tibet, then 3·25 must be equally too low for the deepest parts of the Pacific, which is improbable.

Taking the Pacific as of average depth 4·52 km., the density obtained and used by Washington for the underlying rocks is 3·087. This can be interpreted in various ways. One interpretation and perhaps the most natural out of an infinite number would be to assume beneath 4·5 km. of sea-water a column 55·5 km. thick, made up of x km. of basaltic material of density 3·0, and y km. of peridotite of density 3·4. Solving, we find $x = 43{\cdot}5$ km. and $y = 12$ km. A possible check on the general validity of this type of deduction is afforded by the results of Angenheister[1] on the thickness of the sub-Pacific " crust " as determined by earthquake records. He found a level of discontinuity at 41 km. It is not certain whether the change at that depth is one of state or composition, but the latter seems more probable, and to that extent Washington's figures appear to be supported in an absolute as well as a relative sense.

Beneath the surface of Eurasia Angenheister found a level of discontinuity at an average depth of 28 km. In the same way we may correlate this with the change in depth from granite to basaltic material. Taking the average densities at 2·64 and 3·0 respectively, the average for the isopiestic column is almost exactly 2·8—very close to Washington's figure of 2·79 for areas of average altitude above sea-level. Unfortunately seismological methods and data are still so unsatisfactory, a defect that further work will certainly remove, that results such as Angenheister's cannot be relied upon unless they happen to be supported by converging evidence from other sources. According to Mohorovičić,[2] the average velocity of longitudinal earthquake waves in the outer 60 km. of the continental lithosphere is 5·8 km. per second. The velocities of longitudinal waves in granite, calculated from the densities and elastic constants, are as follows :—

Pressure.	*Corresponding Depth.*	*Velocity in Granite.*
Atmospheric.	Surface.	4·6 km./sec.[3]
2,000 megabars.	7 kms.	5·6 km./sec.[4]
10,000 megabars.	35 kms.	5·9 km./sec.[4]

[1] *Nachr. Ges. Wiss. Göttingen, math.-phys. Kl.*, 1921, p. 21.
[2] *Beit. z. Geophysik*, xiii, 1913, p. 217, and xiv, 1914, p. 188.
[3] H. Jeffreys, *The Earth*, 1924, p. 180.
[4] L. H. Adams and E. D. Williamson, *Journ. Franklin Inst.*, vol. cxcv, 1923, p. 520; and *Smithsonian Rep. for* 1923, 1925, p. 250.

From the seismographic records of the Oppau explosion of 1921, Dorothy Wrinch and Harold Jeffreys found the velocity of the longitudinal waves to be 5·4 km. per second.[1] Here the origin was at the surface, so that the result is unusually valuable, as no error is introduced by ignorance of the focal depth. Comparison between these data and the conclusion arrived at by Mohorovičić strongly suggests that the outer shell is not only granitic but that the granitic layer is, on an average, considerably thicker than has generally been supposed. It further suggests, as Grenville Cole and Mennell and some other geologists have thought probable, that in depth the granitic rocks may become more felsic and consequently of lower density, and not, as is commonly assumed, more mafic. Otherwise it is difficult to understand why the velocity does not average higher than 5·8 km./sec. over such a range of depth as 60 kms. Beyond a depth of 60 km. the velocity rises to 7·9 km. per second, according to Mohorovičić, a figure that differs but little from that given by Professor C. G. Knott in his well-known table of velocities.[2] It also corresponds well with the assumption that the rocks there are of the physical nature of peridotite. However, no more can be concluded from the comparison of the above data than that the granitic shell and the underlying basaltic layer are both comprised within the outer 60 km. of the continental lithosphere.

On page 179 of *The Earth*, Jeffreys suggests an argument that leads to a rough estimate of the thickness of the granitic shell, and this I have here modified by the introduction of additional data. The *long* waves from the Oppau explosion had an average velocity of 3·8 km. per second. The calculated velocity of the corresponding transverse waves is 3·8/0·92, or 4·1 km. per second, characteristic of a depth of 30 km. according to Knott's results; and characteristic of basic rocks at a pressure corresponding to 35 km. depth or more, according to the data recorded by Adams and Williamson. Thus it would seem that around Oppau the basaltic layer is in place beneath a depth of 30 to 35 km.

At Nördlingen the first train of long waves followed very closely on the transverse or distortional waves, and their velocity was therefore very little less than that of the transverse waves, a velocity determined by Wrinch and Jeffreys as 3·1 km. per second. This is also the figure given by Adams and Williamson for the velocity of transverse waves in granite under moderate pressure. The wave length of the long waves was found to be from 6 to 9 km., and the thickness of the granitic layer, to which the long waves recorded at Nördlingen were presumably confined, must have been of the order of a few wave lengths, or say about 27 km. Jeffreys concludes that the thickness of the granitic shell is between 10 km. and 30 km., and favours an estimate of 15 km. This I believe to be an under-estimate, even on his own data, and

[1] *Roy. Astr. Soc. Monthly Not.*, Geophys. Suppl. I, 1923, p. 15.
[2] *Proc. Roy. Soc. Edin.*, vol. xxxix, 1919, p. 158.

I should prefer to adopt limits of 25 and 30 km. as more probable, particularly as the important work of Mohorovičić lends support to estimates even higher than 30 km.

Evidently no single line of seismological research permits altogether conclusive interpretation. The discussion does seem to show, however, that the results of Angenheister, giving an average thickness of 28 km. for the granitic shell of Eurasia, corresponds fairly well with such checks as are available. In a well-known estimate Oldham has deduced the thickness of the continents to be about 30 km.

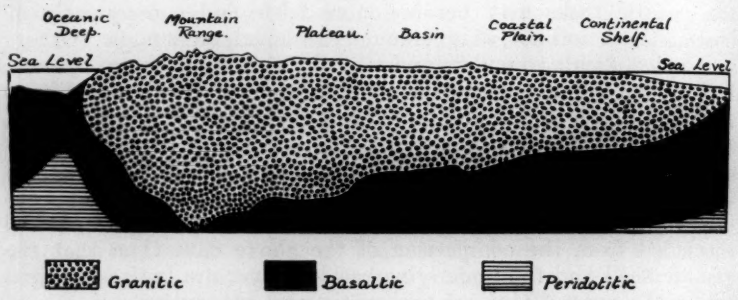


FIG. 1.—Diagrammatic section to illustrate continental and oceanic sub-structures. The horizontal and vertical scales are the same, the distance between sea-level and the base (the level of isostatic compensation) being 60 km. The length is 265 km., but to represent continental dimensions in better proportion ten times that length would be more appropriate.

Combining the seismological data with Washington's density results and the principle of isostasy, a first crude model of continental and oceanic sub-structures like that shown in section in Fig. 1 may be arrived at. Intermediate types of rocks are omitted in the interests of a clear diagrammatic representation. According to this interpretation the average continental thickness is the mean of a varying series of thicknesses, to be correlated with elevation and varying from zero in the deep oceans, to 28·7 km. under the continental shelves and rising exceptionally to as much as 65 km. or more in high plateau regions like that of Tibet. In each locality the pressure on the layer at a depth of 60 km. below sea-level is approximately 172 of the units obtained by multiplying thickness in kilometres by density.

THE GRANITIC LAYER OF THE CONTINENTS.

In attempting to calculate the temperatures at various depths the chief difficulty is now to decide what content of the radioactive elements should be assumed. The problem is, strictly speaking, insoluble, since we do not and cannot know the exact distribution of these elements in depth. Certain hypothetical examples may be considered, however, and so far as these are confined within the range of ascertained data, they may be expected to give an

approximate perspective of the actual conditions. Taking Tibet as an extreme case under which the granite layer may be as much as 60 km. thick, the average radioactivity of granite would maintain a basal temperature of over 4,000° C. even if there were no source of heat at still deeper levels. This figure may be rejected as impossibly high. Fortunately the figures already cited on page 509 show that the radioactive content of granites ranges widely, and if instead of the average only thirty per cent of this amount were assumed, the temperature at the base would be reduced in a similar proportion to 1,200° C., an estimate that seems more reasonable. It may be, indeed, that one of the conditions that have made possible the exceptional heights of the Tibetan and Himalayan regions is the low radioactivity of their underlying rocks.

It is not difficult to show that the granitic masses of the continents may vary very widely in thickness from place to place and still remain solid throughout. The heat lost from each sq. cm. of a continental area is given in calories per second by the product of conductivity and thermal gradient.[1] Taking these respectively as 0·006 c.g.s. units and 0·00032 c.g.s. units, the heat loss is found to be 0·00000192 cals. per second. For a continent of thickness D cms. the heat generated in each column of unit cross section is AD cals. per second, where A is the heat generated from each cc. of the underlying granite in cals. per sec.[2] For continued stability the condition is clearly that all the heat generated throughout the granite should be lost at the surface, i.e. $AD = 0{\cdot}00000192$ cals. per second. The following table shows the values of A for different thicknesses :—

Thickness, D.		*Output of Heat, A.*	*Corresponding types of known granites.*
Cms.	*Kms.*	*Cals./sec./cc.*	
1,000,000	10	192×10^{-14}	Aar Massif.
2,000,000	20	96×10^{-14}	Average.
3,000,000	30	64×10^{-14}	S. and E. African.
4,000,000	40	48×10^{-14}	Scottish.
5,000,000	50	38×10^{-14}	Indian.
6,000,000	60	32×10^{-14}	
8,000,000	80	24×10^{-14}	Antarctic.

It is clear that in so far as all the above figures can be matched by the data for existing granites, there is nothing inherently impossible in the assumption of a variable granitic layer rising locally and exceptionally to 60 km. or more in thickness.[3] As Joly has pointed out, if the granite should anywhere become too thick for continued stability the base would fuse, and the melted materials would then tend to float laterally upwards along the

[1] For a good recent discussion of thermal gradients and their increase in depths near the surface, see R. Daly, *Am. Journ. Sci.*, v, 1913, p. 349.

[2] For values of A see Part I, 1915, p. 66.

[3] For a discussion of thermal gradients in this connection see H. H. Poole, *Phil. Mag.*, Sept., 1923, p. 406.

sub-continental surface. They would also tend to work their way up through fissures and by stoping. Fusion of the basal continental rocks would also be favoured by conduction from any temporary excess of heat in the underlying basaltic zone. Such processes would be most likely to occur during and after periods of crustal thickening by geosynclinal sedimentation and mountain building. The evidence that batholithic invasions, and great lateral injections of granite, have, in fact, this time-relation to periods of folding and overthrusting is well known, and has been partly summarized by Daly in his *Igneous Rocks and Their Origin* (1914, p. 98). In general then, the present continental thickness at any given place should not appreciably exceed that which can remain solid, the maximum possible thickness being everywhere determined by the radioactivity of the rocks. The thickness may, of course, be less than the maximum possible, especially beneath the continental shelves and slopes.

The Basaltic Layer.

Passing now to the basaltic layer beneath the continents, it is easy to see that the radiothermal energy must there be almost entirely conserved, and that in time latent heat will accumulate sufficiently to promote fusion. Beneath the oceans the granitic covering is assumed to be practically absent, and consequently the accumulation of heat, to be possible at all, must take place beneath a considerable thickness of the basaltic layer itself. The problem of calculating the temperatures in depth is complicated beyond hope of accurate solution by effects due to the former history of the basaltic layer. However, an extreme case will serve to show that fusion must occur here as well as beneath the continents. Instead of taking the average radioactivity of basalt and peridotite as being respectively characteristic of the basaltic and peridotitic layers, let us suppose that the basaltic layer at its upper surface has a heat output per unit volume of only 20×10^{-14} calories per second, falling off to half this amount in 42 km., where peridotite is assumed to begin. Then the formula $\theta = \frac{A}{a^2K}(1-e^{-ax})$ gives the temperature θ at any depth x. The value of a is one-third of Adams' value, because here the heating effect falls to one-half in 42 km. instead of in 14 km., that is, $a = 1{\cdot}67 \times 10^{-7}$. At the base of the basaltic layer such conditions would give a temperature of 1060° C., maintained by radioactivity alone. To this must be added a temperature depending on the time during which the basaltic rock has cooled from its last state of fusion. If the material had been cooling for 1,600 million years the temperature inherited from its original state would still amount to about 400° C. If the material had cooled during a shorter period, this temperature would, of course, be higher. The total temperature in the case under discussion must therefore tend to a limit of at least 1,500° C., and this

is ample to promote fusion even under the high pressure of a 42 km.-thick covering. Since there is no reason to suppose that the radioactivity really is limited to the extent assumed in this example, the actual heat output must be still greater. The general statement may therefore be made with some confidence that the basaltic layer in every part of the earth, whether rich or poor in the radioactive elements as judged by surface samples, must sooner or later become molten somewhere below the surface. This is a conclusion that cannot be avoided by any known possibility if it be admitted that the argument of Part IV is sound; and as is now well known, it is a conclusion that has already been reached by Professor J. Joly.[1] According to Joly, however, the basaltic layer may be very much thicker than is here thought probable. Indeed, his writings imply the possibility of its being over 100 km. in thickness, a suggestion that seems to be at variance with the known velocities of earthquake waves that have penetrated to depths greater than 60 km. unless we assume with Goldschmidt[2] that the typical material there is eclogite.

The evidence already submitted in this paper suggests that the basaltic layer is nowhere more than about 42 km. thick, and if this deduction be correct, the difficulty of getting rid of the embarrassing excesses of heat involved in Joly's basaltic layer is considerably eased. Nevertheless the difficulty remains, for if a world-wide basaltic magma can come into existence after the accumulation of heat generated by the radioactive elements it must have done so already, and it must have cooled down again since at least the outer half of the earth is now effectively solid. Joly's inspired contribution to the whole problem has been not only the frank realization that fusion must occur and that the earth has not cooled continuously, but also the visualization of a process whereby the excesses of heat can be periodically discharged.

As soon as a world-wide basaltic magma has been formed, tidal action starts a slow westerly drift of the still solid crust, and the deeper, possibly superheated magma from beneath a continental area thus comes to underlie the ocean floor to the east. Gradually the ocean floor is stoped and melted away from below until the increasingly rapid loss of heat into the ocean overtakes the process and brings it to an end. As a result of tidal currents and convection in the magma, accompanied by the sinking of solid blocks and newly formed crystals, reconsolidation then begins, mainly from below upwards. The continents in their westerly drift are gradually grounded on a solid foundation out of which any residual fluid would soon be squeezed upwards or laterally. The lateral movement is thus brought to a close with the substratum in a solid state as it is to-day. Each level of the basaltic layer which has been fused

[1] *Phil. Mag.*, June and July, pp. 1167 and 170, 1923.

[2] *Vidensk. Skrift. I. Math. Nat. Kl.* Kristiania, No. 11, 1922, No. 3, 1923, and No. 2, 1924.

is then left at the temperature corresponding to its solidification point at the pressure there obtaining, and the cycle whereby the internal excess of heat is accumulated and lost is completed.

It can easily be shown to be improbable that the continents can ever have floated freely in a basaltic magma, for had they done so the ocean waters would have submerged them to a depth of 1,500 metres.

Let the average depth of the ocean above the basaltic magma be y, and that above the continents x. Then taking the average thickness of the continents as 28 km., that of the magma down to the base of the continents will be $(28 + x - y)$ km. By the principle of Archimedes we then have

$$x + (2{\cdot}6 \times 28) = y + 2{\cdot}75\ (28 + x - y) \quad . \quad . \quad (1)$$

where 2·6 is the density of the continents and 2·75 that of the magma. Further, assuming that the volume of sea-water remains constant and that the oceanic area is about twice that of the continental area, we have

$$2 \times 4{\cdot}4 = 8{\cdot}8 = 2y + x \quad . \quad . \quad . \quad . \quad (2)$$

where 4·4 is the present average depth of the oceans. Solving, we find $x = 1{\cdot}47$ km., and $y = 3{\cdot}67$ km.

It is, I think, safe to say that such a general submergence of the continents as a whole has rarely, if ever, taken place.[1] It would imply the submergence of over 80 per cent of the present land areas, and no palaeogeographical maps show more than 40 or 50 per cent. This implies that only about a third of the ocean floor down to the base of the continents can ever have been fused at any one time. It would seem then, that whatever mechanism be adopted for disposing of the excess of heat, it should be such as to permit solidity to an effective thickness of 14 or 15 km. in the outer 23 km. of the sub-oceanic basaltic layer.

Arising out of the above paragraph there is a further point of importance. At present there appears to be an average of 32 km. of basalt beneath the continents and 41 or 42 km. beneath the oceans. If at any time fusion became laterally continuous all over the earth, then the base of the molten layer would tend to become a surface of gravitational equi-potential. A new isostatic level would come into existence. Thus, at a time of maximum fusion the thicknesses of the basaltic layer would tend to become 23·7 beneath the continents, and 47·3 km. beneath the oceans. This shows that when the excess of heat is at its maximum there will be lateral currents within the earth from continental areas, where the heat cannot escape, to oceanic areas, where it can escape easily. Similarly it can be shown that from thick mountainous regions currents will flow towards regions where the continents are thinner.

[1] Certain areas may have sunk and disappeared as land, and others like Barbados and Borneo may have been deeply submerged and have risen again with a layer of deep-sea deposits.

The oceans are fully competent to carry away all the excess heat from the basaltic layer, provided it can reach the submarine surface. The heat generated within each cubic centimetre of average basalt is about 27×10^{-14} cals. per second. The total heat from the whole basaltic layer is then $4{\cdot}7 \times 10^{-12}$ cals. per second. Great as this quantity of heat may be, it would take the accumulation of six or seven thousand years to raise the temperature of the oceans by 1° C. The oceans are therefore available for the reception and disposal of not only all the basaltic heat, but also if necessary a very much greater amount from the underlying peridotite zone.

As we have seen, the process advocated by Joly for discharging the excess of heat implies that the materials of the newly solidified depths should be left everywhere near their fusion points. A very long period would then have to elapse before the latent heat necessary to remelt the basaltic material could be accumulated. Taking the latent heat of basalt as 270 calories per cc., the period required to accumulate this quantity of heat is easily calculated to range from 15 to 45 millions of years according as the radioactivity is high or low. (See Table, p. 509.) At the end of any fraction of the appropriate period the same fraction of the material would be fused, and the remaining parts would form a solid framework to which latent heat would still have to be supplied before it could change its state. But long before the whole could become fluid the framework might break down mechanically, and a sufficient quantity of the fluid fraction might flow together into a continuous layer to permit the tidal drift of the outer shell to begin and the escape of excess heat into the oceans. On an average the maximum period for a complete cycle to run its course would be about 30 million years, but evidently the actual period would generally be less, for as soon as the tidal drift tended to begin in one area it would facilitate the mechanical breakdown of the substratum in neighbouring regions where it might be only partly fused and therefore more resistant.

Epochs of Earth-movement

Here we can begin to test the theory in its relation to geological history. As Joly has shown, when fusion becomes laterally continuous the continents must sink a little, and transgressional seas spread over the lower levels of the lands. Contemporaneous vulcanism is facilitated by the cracking of the crust under tension due to the expansion occurring beneath it. The oceanic areas in particular are increased in area, and the tension clefts are filled up and healed by intrusions of magma, so that the increase of area becomes permanent. As consolidation begins the increased area has to settle down on the contracting substratum, and a certain amount of folding and thrusting must then occur in areas of weakness. Finally, isostatic readjustment involves the raising of the continents

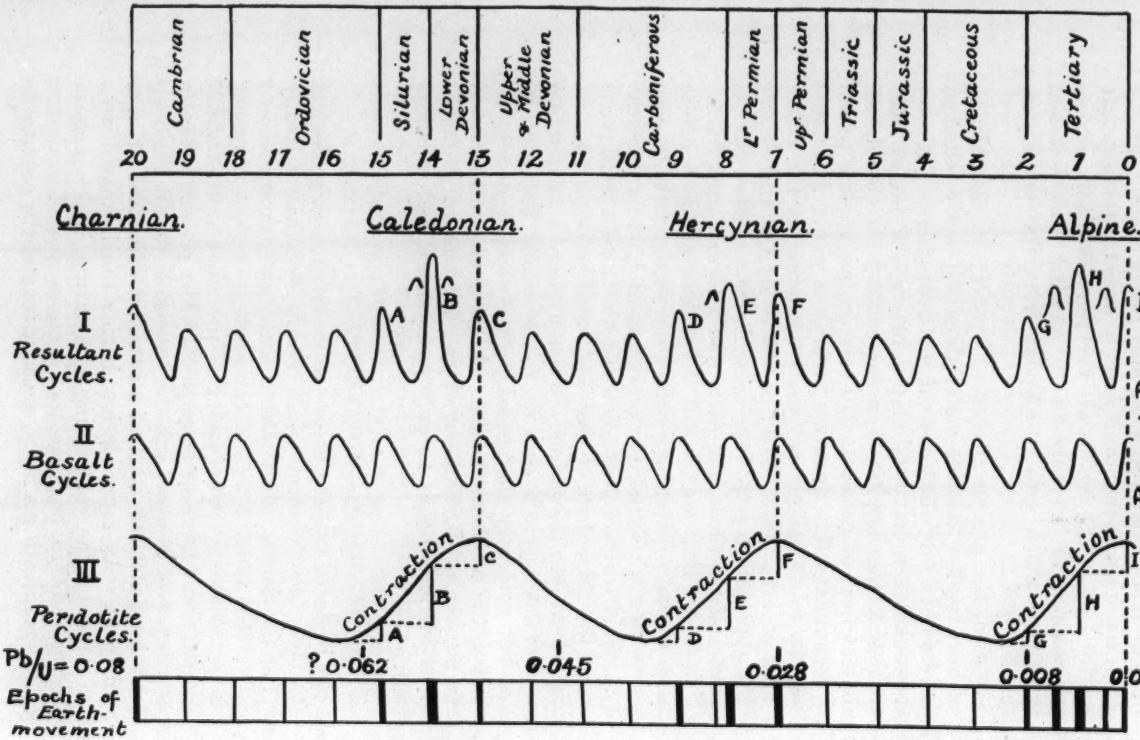


FIG. 2.—Diagram showing in idealized form the cycles of earth-movement since the close of the Pre-Cambrian (I), and their relation to cycles of fusion and consolidation in the basaltic layer (II), and in the assumed peridotite zone (III). The outstanding epochs of mountain-building are correlated with the times when the peridotite zone was contracting. Thus, the contraction represented by A is superimposed on the basaltic contraction of the same epoch to give the Taconic folding. Similarly, B gives the Caledonian compression, and so on through the series lettered. Lead-ratios

relative to the now thickened ocean floor, and the seas retreat from the lands they had previously invaded.

Since the beginning of the Cambrian period this cycle seems to have taken place altogether about twenty times. In the following

list I have gathered together in support of this statement such data as are known to me. Only the places where uplift or emergence or mountain-building have occurred at the epochs named are recorded, and the epochs are numbered to correspond with the numbers on the time-scale of Fig. 2.

20.—Final Pre-Cambrian movements.

19.—*Mid-Cambrian*: emergence and shallowing in Europe and North America.

18.—*End Cambrian*: Green Mts., Vermont, Bohemia.

17.—*Lower Ordovician*: North America, China, and Central Asia.

16.—*Middle Ordovician*: Britain and North America.

15.—*End Ordovician*: Britain, Taconic in North America, Andes, Australia.

14.—*End Silurian*: main Caledonian movements, Britain, Scandinavia, Spitzbergen, Greenland, Urals, Central Asia, Sahara, South America, Australia.

13.—*Early Devonian*: Britain, Central Europe, North America.

12.—*Mid-Devonian*: Britain, Vosges, Caucasus, Urals, Alaska, Australia.

11.—*End Devonian*: Britain, Central Europe, Central Asia, South Africa, Australia, Appalachians.

10.—*Early Carboniferous*: Central Europe, Urals, North America.

9.—*End Lower Carboniferous*: Britain, Central Europe, Central Asia, Appalachians, Australia.

8.—*End Upper Carboniferous*: Main Hercynian movements, Britain, Central Europe, Urals, Central Asia, Arkansas, India, Argentine, Australia.

7.—*Lower Permian*: Britain, Central Europe, Urals, Thian Shan, Pyrenees, Appalachians, Colorado, New Mexico, Argentine.

6.—*End Permian*: Britain, Pyrenees, Urals, Donetz, Argentine.

5.—*End Triassic*: Urals, Caucasus, Donetz, Carpathians, China, United States, Argentine, South and East Africa, Australia, Ceylon.

4.—*End Jurassic*: Britain, Crimea, Gobi Desert, Nevada, Japan, Atlas Mts., New Zealand.

3.—*End Lower Cretaceous*: Britain, Urals, Donetz, Asia Minor, Pacific Ranges of North America, Australia, New Zealand.

2.—*End Cretaceous*: Britain, Central Europe, Caucasus, Donetz, Palestine, Arabia, Dinaric Alps, Malay, Sumatra, Australia, New Zealand, East Africa, Laramide of the Rockies, North America.

1.—*Alpine movements of the Lower Tertiary, End Eocene, and Oligocene*: Britain, Pyrenees, Alps, Himalayas, East Asiatic Islands, Alaska, Northern Rockies, Central America, uplifts in Australia, and East Africa.

0.—*Alpine movements of the later Tertiary up to the present day*:

Britain, Jura, Alps, Carpathians, Caucasus, Donetz, Himalayas, Malay, Dutch East Indies, Festoon Islands of the Pacific, California, Antilles, Australia, New Zealand.

It will be clear from the above list, and it is, indeed, a fundamental fact of geological history, that the movements have not been always and everywhere of the same intensity. The slight changes of level of the Cambrian are of a very different order of magnitude from the world-wide compression and uplift that occurred at the close of the Silurian. Obviously the same process cannot be invoked to explain both. If the fusion of the basaltic layer alone controlled geological history then the graph representing the sequence of subsidence and emergence in time would be ideally like that drawn in Fig. 2, II. A closer approach to a true representation is attempted in Graph I, where the Taconic-Caledonian, the Hercynian-Appalachian, and the Laramide-Alpine mountain-building epochs are given greater prominence. The conspicuously great amount of compression effected during these epochs suggests that the cooling and consolidation of the magma below was then taking place through a far greater thickness than that of the comparatively shallow basaltic layer. Joly considers that the latter may fuse and solidify through a depth of over 100 km., and by this assumption he obtains ample contraction to explain all the great mountain ranges of the past and the present. The assumption, however, not only fails to correspond with the data of seismology, but it also fails to explain the minor cycles between the great orogenic epochs. It seems to me more in keeping with probabilities to refer the latter to the changes taking place in the peridotite which here is supposed to underlie the basaltic layer.

The Peridotite Zone.

In order to derive Graph I from Graph II it is necessary to superimpose upon it the effects of contraction and compression due to a series of longer and more deep-seated cycles like that represented in Graph III. This I interpret as meaning that the deeply buried peridotite with, as we should expect, a low content of the radioactive elements, goes through a similar alternating process of fusion and consolidation but with a period that is many times longer than is required for a basaltic cycle to run its course. Unfortunately, it is difficult to estimate the probable period by a direct appeal to calculations based upon the radioactivity of known samples of peridotite. In the case of basalt this difficulty does not arise, for the great basaltic flows that have flooded the surface can be explained only on the assumption that they are fair samples of the basaltic layer beneath. With peridotite, however, not only are the data scanty but we have no certain means as yet of distinguishing those peridotites that are merely the result of differentiation, taking place in basaltic magma that has invaded

the outer shell, from others that may be primary in the sense of coming directly from the underlying peridotite zone. Hydrostatic considerations moreover make it practically impossible for primary peridotite magma to penetrate the granitic shells of the continents, though it is just possible that it may reach the outer surface of the ocean floor.

All that we know with certainty is that peridotite contains less uranium and thorium than basalt. Dunites from Rum,[1] Styria, and New Zealand contain respectively 0·33, 0·52, and 0·42 $\times 10^{-12}$ grs. of radium per gm. of rock, and correspondingly low amounts of thorium.[2]

A hypersthenite from Mysore contains as little as 0·06 $\times 10^{-12}$ grs. of radium per gm.[3] In some determinations carried out at the Imperial College in 1914 by the late Lieut. George Kirby and myself on the radium content of various rock-forming minerals, we found that a composite sample of olivine from seven different localities gave 0·24 $\times 10^{-12}$ grs. per gm. Fayalites from three localities gave 0·67 $\times 10^{-12}$ grs. per gm., indicating that the forsterite-rich olivines are poorer in radium than those which contain iron.

When both the basaltic and peridotitic layers are fused at the same time there must necessarily be some exchange of material between them. Crystals of olivine forming in the basalt will sink down into the peridotite magma, and the latter will be displaced upwards in proportion. On the whole one would anticipate that this process would have tended to impoverish the peridotite zone in the radioactive elements from a very early period. There can therefore be no serious objection to the view that the period required to fuse peridotite may be many times longer than that required in the case of the basaltic layer. In Graph III, the period of the whole cycle attributed to peridotite is found to be six or seven times as long as that of each basaltic cycle. This implies a radium content of about 0·17 $\times 10^{-12}$ grs. per gm., and a similarly low thorium content. More probably radium would be more abundant, and thorium less abundant. Even with these small quantities the difficulty of getting rid periodically of the excess of heat is a formidable one. With much greater quantities, such as are found in stony meteorites, the interior would probably remain permanently fluid through a considerable depth, and as we know that it is not so at present the small radioactive content implied in Graph III receives indirect confirmation.

The general argument remains true even if we assume that the density and seismological data would be satisfied as well by eclogite as by peridotite. In so far as meteorites are held to give a clue to the kinds of material within the earth the eclogite theory receives no support, though it must be remembered that the pressure within

[1] R. J. Strutt, *Proc. Roy. Soc.*, A. 1906, p. 479,
[2] J. H. J. Poole and J. Joly, *Phil. Mag.*, Nov., 1924, p. 829.
[3] W. F. Smeeth and H. E. Watson, *Phil. Mag.*, Feb., 1918, p. 213.

the parent-body or bodies of meteorites may never have been so high as that attained beneath the basaltic layer of the earth.

The combined activities of two layers of different composition and physical properties appear to give a rough approximation to the sequence of earth-movements. In Graph I the changes referred to the basaltic cycles alone are still too regular to match the facts in detail. Some of the cycles should be shorter and others longer, and the amplitude of subsidence and uplift should also vary both in place and time. The data are themselves sufficiently elastic to permit wide fluctuations, and the interaction of the two layers would produce further irregularities. But all such variations are beyond the possibility of calculation. All that is attempted here is to approach a first approximation, and though the results differ from reality, as all idealized and averaged generalizations must, they are so remarkable that they seem worthy of careful consideration.

The Relation to Geological Time.

Joly correlates his periods of basaltic consolidation with the outstanding epochs of mountain-building. He recognizes three or four complete cycles since the close of the Pre-Cambrian, according as the Laramide "revolution" is regarded as a forerunner of the greater Alpine orogenesis, or as a separate event co-equal with the Hercynian or the Caledonian. As he allows about 40 million years for each cycle, the time required for three or four cycles is 120 or 160 million years; and for the whole duration of earth history since the Laurentian about 240 million years is suggested. So far as I know, Joly, among authorities on radioactivity, stands alone in his adherence to such low estimates of geological time. The evidence on which he relies can be interpreted in other ways, but until work now in progress on the disintegration of uranium and its relations to actinium is completed, the general problem cannot be regarded as settled. I can, however, find no reason for suspecting that the lead-ratios of radioactive minerals can possibly give results more than a few per cent too high.

According to my own interpretation, the basaltic cycles, distributed as in Fig. 2, require an average period of rather less than 30 million years each. Consequently since the close of the Pre-Cambrian the time elapsed should be of the order of, but less than, 600 million years. The late Joseph Barrell,[1] in the most careful study of geological time yet published, arrived at the conclusion that since the beginning of the Cambrian the minimum duration was 550 and the maximum 700 million years. The results of more recent research would slightly reduce these limits.

The nearest approach to the close of the Pre-Cambrian is probably afforded by the uraninite of Katanga. This mineral gives a well-confirmed lead-uranium ratio of 0·08. Thorium is absent, and from

[1] *Bull. Geol. Soc. Am.*, vol. xxviii, 1917, p. 885.

its atomic weight the lead is known to be wholly derived from uranium. To a first approximation the age is therefore $Pb/Ur \times$ 6,600 million years, that is 528 million years. For the Middle or late Devonian radioactive minerals of the Oslo (Kristiania) District the average ratio is 0·045. For the late Carboniferous or early Permian pitchblende of Joachimsthal the ratio is 0·042, but one-third of the lead, as proved by its atomic weight, is ordinary lead. Correcting for this, the ratio reduces to 0·028. This correction finally removes the former difficulty that the Middle Devonian seemed to be of practically the same age as the early Permian. The uraninites of North Carolina, which are probably of Pennsylvanian or Permian age, give exactly the same corrected ratio. Uraninite from Gilpin County, Colorado, gives a ratio of 0·008, and the age is about that of the Laramide orogenesis. Brannerite from Idaho gives a ratio of half this amount, and the age is either late Cretaceous or late Oligocene, the ratio itself suggesting the latter of the alternatives.

When all the ratios are inserted in their most probable positions in the time-scale of Fig. 2, they converge in giving for each basaltic cycle an average period represented by the ratio 0·004, that is, a period of 26·4 million years. The agreement with the period calculated from the latent heat is very close, and the conceptions embodied in Fig. 2 therefore stand or fall with the longer estimates of geological time that are based on lead ratios. If those estimates be independently proved correct, then the conception of the basaltic cycles receives support of the most convincing character.

The outstanding orogenic epochs are here correlated with peridotite cycles having periods represented by the ratios 0·024 to 0·028. The chief data are as follows :—

Lead Ratios.	*Orogenic Periods.*	*Intervals.*
0·000	Present Day.	0·028
0·028	Hercynian .	
No data.	Caledonian .	0·052
0·080	Late Pre-Cambrian	
No data.	Sub-Jotnian .	0·050
0·130	Post-Kalevian .	
0·156	Post Laurentian .	0·024

It is worth noticing that the earliest well-established interval is 0·024, that the next two pairs give four intervals of 0·025 and 0·026, and that the latest is 0·028. This may be purely accidental, but it may also correspond with the fact that, since the radioactive elements are constantly disintegrating, they must have been originally more abundant than they are now. During the period represented by the ratio 0·156, uranium must have been reduced in the proportion 1·175 to 1. The intervals of the cycles should therefore have increased in the proportion of 1 to 1·175, and they appear to have done so.

Recent years have witnessed very great changes of opinion

as to the evolution and structure of the earth. Jeans and Jeffreys[1] have liberated the newly-born earth from the solidity imposed upon it by the Planetesimal hypothesis. Our French colleagues have always had a peculiar faith in the mobility of the inner earth, and Joly[2] has now shown us that their faith may be justified. The slowly working leaven of radioactivity enables the earth to renew her youth periodically and there is no sign that the calamity of permanent rigidity recently alluded to by Professor W. A. Parks[3] is likely to overtake our planet for many thousands of millions of years.

The Northern Range of Trinidad.

By C. T. Trechmann, D.Sc., F.G.S.

(PLATE XXV.)

Introduction.

THE northern mountain range of schistose rocks of the Island of Trinidad reaches an altitude of 3,012 feet in Mount Tucutche and consists of a wild and tumbled mass of ridges with deep intervening valleys clothed from top to bottom with tropical vegetation, the abode of a practically undisturbed fauna and flora. Westwards the range is continued in the rugged and precipitous islands of Monos, Huevos, and Chacacare between which are the Bocas through which ships pass in entering the Gulf of Paria from the north. The entrance to the Gulf is famous for its scenic beauty. North-eastwards the schist-range reappears in the island of Tobago, but no limestones are reported to occur among the rocks there. Westwards the high range of schistose mountains continues along the northern coast of a great part of Venezuela,[4] and over 800 miles further west at Santa Marta in the Republic of Colombia I have seen a series of schists very similar in lithology to those that form the northern range of Trinidad.

This northern range comprises the Caribbean Group of Wall and Sawkins,[5] and these authors give a very good and somewhat lengthy description with illustrations of this series of beds. They consist of a varied series of micaceous or ferruginous schists and shales enclosing numerous quartz beds and veins, sandstones, and other similar rocks, together with extensive beds of both crystalline and compact limestone. Wall and Sawkins failed to find fossils in any of these beds, and so do not attribute the series to any definite

[1] See chaps. i and ii of *Evolution in the Light of Modern Knowledge*, 1925.

[2] Since writing this paper Professor Joly's book *The Surface History of the Earth* has appeared. In it many of the problems and difficulties are discussed at greater length than in the original *Phil. Mag.* papers of June and July, 1923.

[3] *Nature*, 19th September, 1925, p. 432.

[4] See L. V. Dalton, Geology of Venezuela, Geol. Mag., Dec. V, Vol. IX, May, 1912, p. 203.

[5] Report on the Geol. of Trinidad, *Memoirs of the Geol. Survey*, 1860, p. 13.

period, but they leave the reader to infer that these metamorphosed beds are not necessarily of Archaean age.

Along the south-western fringe of the range the beds are considerably less altered than they are in the main mass of the northern range. These less altered portions are distinguished on Wall and Sawkins' map as "compact limestones" and include the rocks of Laventille Hill near Port of Spain, the peninsula of Pointe Gourde and several islands in the Gulf of Paria south of the Bocas, namely Five Islands, Diego Island, and Gasparee Island, together with Goose Island off the Venezuelan coast. In the limestones at most of these places, but especially in those at Laventille, traces of fossils have been found. In the more altered schistose limestones in the main range, however, wherever I examined them the chance of finding any fossils seemed practically hopeless. There seems nevertheless to be every probability that the compact limestone is the same bed, only in a less altered condition, as the limestones in the main mass of the schistose northern range.

The late Mr. R. G. L. Guppy, who lived many years in Trinidad, obtained some fossils from the Laventille limestone quarries near Port of Spain which he thought were of Carboniferous age, one of them a fish and the other a cephalopod which he supposed to be a Goniatite. Unfortunately these fossils were destroyed in 1921 when the Victoria Institute of Port of Spain was burnt, and so any direct appeal to them is now impossible.

Mr. E. H. Cunningham-Craig, F.G.S. however, fortunately had an opportunity of examining them and writes concerning them:[1] "The most important organisms discovered are a cephalopod and a fish obtained by Mr. R. G. Lechmere Guppy from limestone quarries near Port of Spain. Mr. Guppy identified the cephalopod provisionally as *Goniatites caribeus* and the fish (an ill-preserved vertebral column with part of the tail) as *Acanthodes elongatus*. In several points, however, the cephalopod differs from a goniatite, having a distinct keel and deeply grooved whorls. The sutures cannot be seen. I am inclined to class it provisionally as an Ammonite of a type not earlier than Jurassic. The fish is too ill-preserved for accurate determination."

After mentioning the occurrence of other fragmentary and minute organisms, Mr. Cunningham-Craig goes on to say, "such evidence, however, as is available, all points in the same direction, and suggests that the northern range is formed of strata not older than Jurassic affected by moderate dynamo-metamorphism."

Comparison of the Northern and Central Ranges of Trinidad.

Mr. Cunningham-Craig, who spent several years in Trinidad and Tobago, thinks that the limestones seen at Laventille, in the Five Islands, Gasparee, Point Gourde, and in almost any valley of the

[1] The Metamorphic Rocks of Trinidad, *Report Govt. Geol. Council Paper*, No. 76, 1907, pp. 5–9.

range are, if not the oldest, amongst the oldest groups of sediments represented, since they occur in the centre of a fan structure with the other sediments folded over them. This conclusion does not seem to conform with the sections of the northern range on Sheet No. 1 as illustrated by Wall and Sawkins, and after my own observations on the beds and a study of the numerous dips given on the map of Wall and Sawkins I am scarcely able to agree with the idea. I feel fairly well convinced that the compact limestones of Laventille and elsewhere represent the same beds as the crystalline limestones in the central parts of the range, but all these limestones seem to be underlain by a great mass of schists and metamorphosed beds and to be rather high up in the sequence, and not in any way the lowest beds.

Mr. Cunningham-Craig in the same paper on the metamorphic rocks of Trinidad adduces various arguments for considering the rocks of the northern range to be the metamorphosed equivalent of those of the central range of Trinidad. These arguments are mostly based on a supposed lithological similarity of the beds of the two ranges, but here again, though I have had a much less prolonged acquaintance with Trinidad than Mr. Cunningham-Craig, I am unable to agree.

The interesting discovery has recently been made of Rudist limestones [1] of approximately Cenomanian age among the complex of beds that form the central range, and I think that if these limestones had formed part of the northern range the presence of such conspicuous fossils would have been traceable.

The beds of the Central range, the Older Parian group of Wall and Sawkins, appear to me markedly different from those of the northern range. For instance, on the west coast of the centre of the island at Point à Pierre they comprise a group of much faulted and crushed more or less steeply dipping shales and sandstones which are presumed to be, but so far as I am aware have not all been definitely shown to be, of Cretaceous age. Among them, however, standing a few yards out from the shore is a large flattened weathered mass of limestone full of a Rudist mollusc resembling a *Caprina*, called *Praecaprina* (?) *pennyi* by Harris; some curious *Turritellae* and other molluscs, all unfortunately poorly preserved. This limestone dips almost vertically, as do the shales in the cliff immediately opposite, which contain small crushed pieces of a similar limestone, evidently a continuation of the larger mass that was once obviously embedded in the shales. This limestone owes its position to crushing action but is apparently not actually in situ, and appears to have been squeezed in from some lower or possibly higher horizon among the shales and sandstones. Near the opposite eastern side of the island in the central range similar beds recur.[2] They may

[1] G. D. Harris and Floyd Hodson, The Rudistids of Trinidad, *Palaeontographica Americana*, vol. i, No. 3, 1922, pp. 119–162.

[2] Some Cretaceous mollusca from this district have recently been described by Mr. R. B. Newton, *Proc. Malacological Soc.*, vol. xvi, pt. iii, pp. 140–8, Dec., 1924.

be seen up stream courses south of the Plum road on the north side of Mount Harris and comprise limestones containing *Rudistae* of the same early age as those of the Stack rock at Point à Pierre, but differing in genera and species. These limestones may be connected with extensive Cretaceous beds below and may have been squeezed up into the position they now occupy, but here again I fail to see any resemblance between the beds of the central and those of the northern range.

DESCRIPTION OF SECTIONS OBSERVED IN THE NORTHERN RANGE.

Some large quarries have long been opened at the base of Laventille Hill on the roadside to the east of Port of Spain. In one of them about 120 feet of alternating massive beds of veined and sheared blue and grey limestones divided by beds of semi-schistose shales are seen. The exposure looks unpromising for fossils, and the manager of the quarry told me that none had been seen so far as he was aware. This is presumably the locality whence Mr. Guppy's fossils were obtained, and possibly a very prolonged search might yield some results.

A short distance away to the north-west, and rather higher up the hill another quarry occurs, and shows about 150 feet of well bedded massive blue and grey veined limestones, separated by about 10 feet of semi-metamorphosed, twisted and slickensided pink and grey shales and thinner partings of the same material. At one place this rock

SECTION OF BEDS AT LAVENTILLE HILL NEAR PORT OF SPAIN.

	Approximate thickness in feet.
1. Rather thickly bedded compact grey limestones, with a bed of slender Nerinaeas near the base and about 15 feet above it a band of ramifying sponge-like organism	30
2. Crushed shale	5
3. Pink, thinly bedded fine grained sandstone dipping more or less north-west at about 30°. The church at the summit of the hill facing the Gulf stands on this bed	10 (?)
4. Massive brecciated partly stalagmitic limestone	30
5. Well-bedded limestone bands, the beds 1–2 feet thick	60
6. A band of sections of Lamellibranchs (*Thracia* ?)	5
7. Massive pink limestones, oolitic in places	20
8. Crushed pink and grey shales, much cleaved and contorted, enclosing small nodules here and there	40
9. Bedded blue limestones, much veined, exposed in a small quarry by the side of the track, with sections of Lamellibranchs (*Thracia* ?)	60
10. Grey and green shales	40
11. Veined limestone	?
12. Massive bedded limestones dipping 30° south-east	40
13. Crushed shale	10
14. Limestones	40 (?)
15. Grey shales	60 (?)
16. Grey well-bedded limestones with intercalated twisted shales, corresponding to the limestones exposed in the large quarries on the roadside	over 50

dips about 65° to the south-east, but elsewhere the dips are not so great. There is no doubt much faulting hereabouts and the beds in both quarries may be the same. No fossils were seen.

The most instructive section, however, is exposed on the road, and other tracks that lead from the base of Laventille Hill opposite Port of Spain up to the summit, which is occupied by a Catholic Church and a prominent illuminated advertisement for cigarettes. I made a somewhat detailed examination of the beds of Laventille Hill.

Gasparee Island and Pointe Gourde.

The limestones of the Island of Gasparee are quite similar lithologically to those that build up the Laventille Hills, but fossils appear to be very scarce. In those portions examined, I only found one or two distorted Lamellibranch valves, and here and there partly silicified bands of microscopically-sized shell and oolite fragments.

The rocks of the island seem to be chiefly massive well-bedded blue and grey limestone, considerably veined with calcite, and much faulted and brecciated in places. The parts I saw dip north or north-west at various angles.

Similar limestones build up the peninsula of Pointe Gourde, which is really an island separated from the land by a swamp, but I was not able to find any fossils there. The foliation planes of the much twisted and veined schists on the main island opposite Gasparee and Pointe Gourde dip towards the south, and seem to pass underneath the compact limestones of the island outliers. This fact, unless there is faulting in between, makes it very improbable that the limestones are among the oldest beds of the northern range.

The Schistose Beds.

The limestones of the central part of the range can be well seen in quarries and other exposures to the north and north-east of Port of Spain at such localities as Diego Martin, the Morne Coco Road, Maraval, Santa Cruz, and other places. Similar schistose limestones are seen near Balandra Bay on the east coast. They are similar in general aspect to the massive limestones at Laventille and Gasparee but metamorphism has progressed much further and the shales have become "schistes lustrées" and the more flaggy limestones are coated and impregnated with talc-mica-schists. An interesting paper on the microscopic structure of these beds has recently been published.[1]

I searched in several localities for fossils, but with no result, though it is possible that traces of fossils may occur in some places. Near Toco in the far north-east of the range the beds, according to Sawkins, are less altered and sandstones and a conglomerate come in.

[1] J. Parkinson, Geol. Mag., Vol. LXII, No. 729, March, 1925, pp. 133–6.

In a stream gorge at Fondes d'Amandes behind Port of Spain micaceous schists of different varieties occur twisted in various directions with large masses of white quartz along the foliation planes and smaller veins of similar material crossing the rock in various directions. The rock, however, still shows traces of its massive original bedding.

Palaeontology.

The fossils found by Mr. Guppy and unfortunately destroyed have already been mentioned. They appear to have come from the base of the Laventille section where, however, my search was unsuccessful. Higher up the hill I was more fortunate, and the sequence of the beds and their fossils I observed there has already been set out. The fossils include :—

Small slender *Nerinaeae.*

Bivalves nearly all merely as cross sections, probably *Thracia.*

A branching or ramifying sponge or coral-like structure.

Microscopic shell and oolitic structures.

Though the occurrence of definite *Nerinaeae* precludes any possibility of these limestones being Palaeozoic, their position in the Mesozoic sequence is not easy to fix, but I think that about middle Jurassic seems their most probable date.

Nerinaea sp. (Pl. XXV, Figs. 2 and 3.)

The Trinidad *Nerinaeae* have a decidedly Jurassic aspect, and seem all to belong to one species. They are rather plentiful in a bed of limestone near the top of Laventille Hill, and occur on the weathered surfaces, the shell having been converted into a mineral resembling Pearl Spar. I have counted seventeen whorls on a specimen ; the earlier nine or ten whorls are platformed and have a conspicuous rounded ridge immediately below the suture and below this ridge the whorls are strongly excavated and have concave sides. These features are still present on the later whorls but become much less pronounced, the ridge becoming smaller and the concavity shallower. Very fine spiral lines appear on the earlier whorls, but the surface of the later ones appear to be smooth. The columella is fairly thick, but the outer wall is thin, leaving a rather capacious living chamber. The outer wall has on its inner side rather below the middle an obtuse projection. The columella has a blunt fold situated rather anteriorly, and behind this and towards the hinder inner angle a sharp forwardly projecting plication. The largest specimens measure about 30 mm. in length and 4·5 mm. in width at the base.

They seem to agree with Section C (*Triplicatae*) of Hudleston (Gasteropoda of the Inf. Oolite. *Palaeontographica*, Part i, No. 4, 1890, p. 194), which have one well-marked fold on the outer wall, one on the lower part of the columella, and one about the junction of the columella with the outer wall, all simple, e.g. *N. oolitica*

Witchell. This is a very numerous section, and includes most of the proper *Nerinaeae* of our Inferior Oolite.

The outer shape of the Trinidad specimens also resembles rather closely that of *N. oolitica* (Pl. xiii, fig. 4*a*, *b*, and *c*), or varieties of that species (pl. xiii, figs. 6 and 7). They may also be compared with *N. weldonis* Hudleston (Pl. xiv, figs. 3 and 4) or *N. zonophora* Hudleston (pl. xiv, fig. 7) both from the Lincolnshire Limestone. *Nerinaea cingenda* Phillips of the Dogger of Blue Wyke on the Yorkshire coast has more whorls and increases very slowly in size, and has two fairly clear folds on the outer wall of the living chamber and a different external ornamentation.

Thracia (?) sp. (Pl. XXV, Fig. 4.)

Part of the limestone at Laventille Hill is full of bivalve shells, but except in one case I was unable to find them in any other condition than that of cross sections on the weathered surfaces. In spite of crushing it is evident that one valve was rather smaller and flatter than the other, and in most of them a shelly thickening of the hinge margin can be seen beneath the beak in both valves. All the sections may belong to one species. That it was a closed or slightly gaping shell is indicated by the fact that some of the shells were only partly filled with limestone like that which forms the rock, the remaining space having been filled up later with infiltrating crystalline calcite.

The single exception referred to above is a weathered left valve with parts of the slightly displaced right valve still remaining. The beak is rounded and rather anteriorly situated, and the left valve shows a thickened process of the hinge line behind the beak resembling the marginal thickening below the hinge in the genus *Thracia*. Immediately below the beak a gap appears, while in front there is a trace of another short marginal thickening of the hinge. The specimen is 23 mm. long, and 18 mm. high, while the sections in the rock measure up to 13 mm. across the valves.

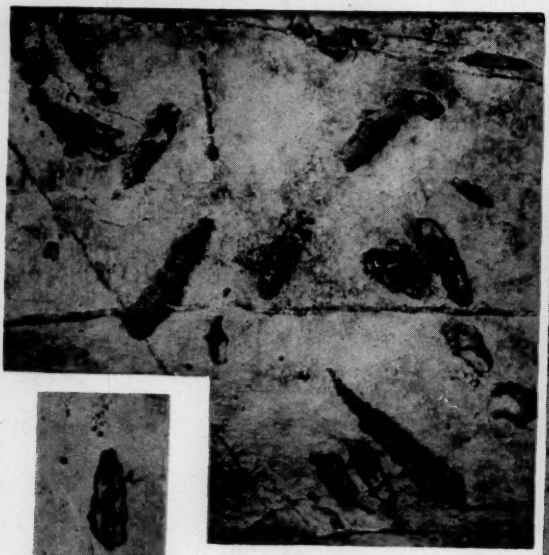
A similar but very poorly preserved bivalve of rather larger size occurs among oolitic limestone on Gasparee Island near Pointe Baleine. It may be a *Thracia*, but no trace of the hinge was seen.

Sponge ?

A branching organic structure occurs near the top of Laventille Hill and extends along the bedding planes, occupying a thickness of 6 inches or more. The branches in cross section are more or less circular with a diameter up to 13 mm., and affect an irregular or wandering habit, being massed together in places. Cross sections on weathered surfaces show here and there traces of concentric growth, but otherwise the structure has been obliterated by recrystallization. The organism may very likely be a branching sponge of the type of *Peronella*, Zittel, or may be a coral resembling in growth habit *Goniocora* Ed. and H. or possibly *Enallohelia* or *Cladophyllia*, whose structure has been destroyed.

1

2



3

C. T. T., photo.

TRINIDAD : VIEW OF THE NORTHERN RANGE.

2, 3. *NERINAEA* sp. 4. *THRACIA* (?) sp.

To face p. 551.]

EXPLANATION OF PLATE XXV.

FIG. 1.—View from Laventille Hill, consisting of compact limestone in which the fossils were found, towards the N.W. looking over part of the town of Port of Spain to the Gulf of Paria. To the right are the schist hills of the northern range of Trinidad. Across the water the peninsula of Pointe Gourde and the island of Gasparee and others, formed of compact limestone, are seen. Still further, hidden by mist, is the Venezuelan coast.

FIG. 2.—Weathered surface of Laventille Limestone with a group of *Nerinaea* sp.

FIG. 3.—*Nerinaea* sp. Laventille Hill. Spiral portion embedded in rock.

FIG. 4.—Weathered surface of Laventille Limestone with sections of Lamellibranchs, *Thracia* (?) sp.

REVIEWS.

MEMOIRS OF THE GEOLOGICAL SURVEY OF GREAT BRITAIN. Palaeontology. Vol. ii, Part v: Fossil Plants of the Carboniferous Rocks of Great Britain. By Dr. ROBERT KIDSTON. pp. 377–522, plates 92–122. Southampton: Ordnance Survey Office. London: E. Stanford, Ltd. 1924. 20*s.* net.

THE sudden death of Dr. Kidston last year occurred when less than half of his great work on the Carboniferous floras of Great Britain had been published, and it seemed that we might be deprived of the greater part of the results which he had accumulated by many years of study and collecting. It is therefore very satisfactory to be able to record the publication of part v of the work, which makes up half of the ten parts promised.

This part deals with a further selection of fern-like plants, some of which are rare and little known, while others such as the genus *Asterotheca* (*Pecopteris*) are common and rich in species difficult to diagnose. Some of the species described are new, while others are of special interest because they have been found in a fertile condition. Some species are almost invariably found in a sterile state, though they belong to genera founded mainly on the characters of their reproductive organs, and in these cases it is most valuable to have Kidston's careful, detailed descriptions of both fertile and sterile specimens, with his discussion of their characters and his admirable figures.

Towards the end of the part the consideration is commenced of that great group of fronds which are generally designated *Pecopteris* when found in the sterile condition. The author adopts the plan of using the generic names founded on the characters of the fructification where such is known to exist, thus many species are freed from the form genus *Pecopteris* and are placed in the genus *Asterotheca*. This procedure should prove of great value in splitting up an unwieldy and unnatural group.

As in the previous volumes lists of synonyms are given and also complete records of the localities and horizons at which each of the species has been found in Britain.

It is greatly to be hoped that it will be possible to continue the publication of this work, and that eventually all the notes and records which Dr. Kidston had collected for the purpose may be made available for use.

JUNGTERTIÄRE CARNIVOREN CHINAS. By OTTO ZDANSKY. Palæontologia Sinica, Ser. C, Bd. 2, fasc. 1. Geological Survey of China. pp. 156, 33 plates, and over 21 text-figures. Peking, 1924.

IN this memoir the author describes thirty-eight species of fossil carnivores, nearly all of which were found in Northern China. Most of them are from the *Hipparion* beds, which are regarded as

being of Upper Miocene age, but some species are believed to be earlier. The occurrence of *Indarctos* (hitherto only found in the Siwaliks and in the Rattlesnake beds of the Johnson-Day River), as well as a species of the genus *Parataxidea*, is cited as evidence that the *Hipparion* beds of Northern China represent the upper part of the Miocene. The presence of the badger-like *Parataxidea* is indicative both of eastern and western connexions, since representatives of this genus have been discovered both in Persia and in the Thousand-Creek beds of Nevada. Two species of fossil hyaenas (*H. variabilis* and *H. honanensis*), both of them probably new, are described, as well as three (or four) species of *Ictitherium*, a kind of primitive hyaena; a new species of marten (*Proputorius minimus*); a true weasel (*Mustela palaeosinensis*); a much larger mustelid, which is called *Plesiogulo brachygnathus*; and another form, *Melodon majori*, which the author suggests may be the ancestor of the modern *Meles*.

In addition to these, the occurrence is recorded of three species of *Machairodus*; a new genus, *Metailurus*, containing two species, one large and the other small; a highly specialized felid, *Dinofelis abeli*, belonging to an entirely extinct branch of the family; and three species of true cats (*Felis*), showing that this genus was contemporaneous with *Hipparion*. The relationships of these and other forms are fully discussed, and their geological significance pointed out. The memoir is illustrated by a fine series of plates, besides some excellent text-figures, and the whole volume represents a vast body of original work.

F. H. A. M.

LUNDY, ITS HISTORY AND NATURAL HISTORY. By L. R. W. LLOYD. pp. xii + 248, 20 full-page illustrations and map. London: Longmans, Green and Co., 1925. Price 12*s.* 6*d.* net.

MR. LLOYD has written an attractive book. The subject matter is about equally divided between the history and natural history of Lundy. The first chapter is archaeological and discusses the evidence relating to the early settlements upon the island. A gigantic tombstone formed of granite and known as the "Giant's Headstone" is described and figured, as well as another "worked" stone (the Stone of Tigernus), believed to date from the middle of the first century. In later chapters the history of Lundy is traced in detail from the time of its presentation to the Marisco family (from whom it passed in 1321) until the present day. In the part dealing with the natural history there is a very full and admirable account of the birds of Lundy, with many original observations on their migrations and other habits. The chapter entitled "Natural Features" will be the one most interesting to the geologist. The island is of igneous origin, with a small area of slate corresponding to the Ilfracombe and Morte beds at the south end. There are intrusive dykes of igneous rock of two classes, as well as numerous small veins. Iron sulphides and oxides are abundant, and there are

traces of copper. The account of the geology is based on the work of de la Beche, D. Williams, Etheridge, and T. M. Hall, to which the author adds observations of his own, with descriptions of the caves occurring round the coast. The book is illustrated by a number of photographs, in which the nature of the rocks is well shown.

F. H. A. M.

The Physical Chemistry of Igneous Rock Formation. A general discussion before a joint meeting of the Faraday, Geological and Mineralogical Societies. Transactions of the Faraday Society, Vol. xx, 1925, pp. 413–501; also issued separately (Gurney and Jackson). Price 6*s.* 6*d.* The contributors to this discussion are: J. S. Flett, G. W. Tyrrell, P. Niggli, W. A. Richardson, J. W. Gregory, J. W. Evans, C. H. Desch, W. E. S. Turner, A. F. Hallimond, and A. Scott.

THE introductory address by Sir John Flett gives a short historical account of experimental petrology from the time of Sir James Hall, while two other papers, those of G. W. Tyrrell and A. Scott, confine themselves to reviews of recent experimental research and some of its field applications.

Other papers with a dominant petrologic theme are comprised under the titles: (*a*) Homogeneous equilibria in magmatic melts; (*b*) Some ultimate problems in petrogenesis; (*c*) Magmatic ores; (*d*) Proposed researches on the chemistry and physics of igneous magmas and rocks.

Of these, the first named, contributed by P. Niggli, is undoubtedly the most valuable. Herein is provided an illuminating and suggestive study of homogeneous equilibria in melts applied to the differentiation of rocks of the Atlantic, Pacific, and Mediterranean suites.

Confessed chemists supply papers on: (*a*) The theory of crystallization in rock magmas, and (*b*) Some physical properties of silicate glasses and their possible bearing on the history of igneous rocks.

It may be doubted whether petrologists will derive much profit from either of these contributions. In the first, the recent work of the Geophysical Laboratory is discussed and criticized, particularly in reference to the fruitful conception of the reaction principle, and it is stated that the adoption of this principle involves the abandonment of the equilibrium diagram.

Petrologists are solemnly asked to return to the problems of igneous rocks in the light of the studies of the crystallization of organic mixtures and salt solutions. In words: "Such a way of regarding magmas is likely to prove more fruitful than the abandonment of the equilibrium diagram and its replacement by a new principle which almost represents a return to the old views of the French school."

Happily for the uninitiated, this extraordinary request is replied to in the discussion from the most appropriate quarter.

The several contributions are punctuated by general discussions, in which expositions of elementary petrology are significantly prominent. It is too much to hope that this symposium will herald a new era of organized experimental research in Britain, nevertheless, if it should have stimulated among physical chemists an active interest in the problems of petrogenesis its labours will have been by no means in vain.

C. E. T.

THE GEOLOGY OF ASCENSION ISLAND. By R. A. DALY. Proc. Amer. Acad. Arts and Sci., Vol. LX, 1925. 80 pp., with 21 plates (one being a contoured geological map).

A PRELIMINARY account of Professor Daly's work on Ascension Island has already appeared in this Magazine; in this paper his results are set out in greater detail, with many beautiful illustrations and seven new rock-analyses. Professor Daly found that Darwin's account of the island is accurate and thorough to a high degree, only needing amplification on modern lines.

The types of lava include a series beginning with olivine-basalt and passing through olivine-free basalt, trachydolerite, andesite (?) and trachyandesite to alkaline trachyte and quartz-trachyte ("rhyolite"). The series is similar to that found at Tutuila (Samoa). The trachytes occur as endogenous domes or crater-fillings, and it is shown that the alkaline types are differentiates of the basalt magma. Fifteen plutonic rock-types were found among volcanic projectiles, as well as highly alkaline amphibole-granites as xenoliths in trachyte. The occurrence of the more acid types of lava is largely attributed to rise of highly siliceous solutions, and much importance is attributed to explosive gas-phases, in combination with gravity, as agents of differentiation, the process being described in general terms as a modified form of the fractional crystallization theory.

R. H. R.

ZEITSCHRIFT FÜR GEOMORPHOLOGIE, Edited by Dr. ANDREAS AIGNER and Dr. JOSEF STINY. Band I, Heft 1, 82 pp. Leipzig: Borntraeger, 1925.

THIS is the first number of a new periodical, intended for the discussion of a variety of problems, mainly of a geographical or physiographical character, for which it is believed no exact place exists in other publications. It is to contain original papers of some length and detailed character, as well as short communications, reviews and reports of the meetings of societies, and bibliographies of recent publications. Each annual volume of about 400 pages will be published at 30 marks.

The first number contains papers on valley-formation, river denudation, and points of Alpine morphology, as well as a number of

short notes on land-slips, earthquakes, and other topics, together with several reviews, largely of works devoted to Alpine regions.

Die Gliederung und absolute Zeitrechung des Eiszeitalters. By W. Soergel. Fortsch. der Geol. und Palaeontol., Heft 13, pp. vi + 127, with 2 plates. Berlin: Borntraeger, 1925.

AMONG the many attempts that have been made to introduce an absolute time-scale into geology the most satisfactory so far have been those dealing with the date of the glaciations of northern and central Europe. De Geer's determinations of the time of the retreat of the ice-sheet in Sweden may now be accepted as established, but this is not the only means open to us for estimating geological time from this point of view. The astronomical methods have also their applications.

In the publication under review the general editor of the series, Dr. W. Soergel, gives an excellent summary of the latest state of our knowledge of the various methods available for estimating the date and duration of glaciations in the later periods of earth-history. Special attention is paid to the theory developed by Koppen and Wegener, largely on the basis of the work of Pilgrim and Milankovitch, which takes into account purely astronomical factors, the inclination of the ecliptic, and changes in the eccentricity of the earth's orbit and heliocentric longitude of perihelion. The dominant factor in the production of glaciations is considered to be the amount of radiation received during the summer half-year. The results of this purely theoretical and astronomical investigation are here correlated with the work of geologists on the number and duration of glacial and interglacial periods in Europe. Special attention is naturally paid to central European glacial stratigraphy, but the concluding section contains a discussion of the bearings of the results postulated on geological investigation in general. This is a most valuable contribution to geological chronology.

Physikalisch-Chemische Mineralogie und Petrologie. Die Fortschritte in den letzten zehn Jahren. By W. Eitel. pp. 174, 53 text-figures. Dresden und Leipzig: Theodor Steinkopf, 1925.

THIS volume is one of a series issued under the general editorship of Dr. R. E. Liesegang. The present volume (Band XIII) by Professor Eitel purports to give the advances within the last ten years in the realm of physico-chemical mineralogy and petrology. The book is divided into two parts, the first dealing with general physico-chemical principles, the second devoting attention to mineral syntheses, investigations on mineral systems, and special sections on gas equilibria, hydrothermal syntheses, weathering, colloid mineralogy, salt petrography, etc., with a final survey of the advances in rock-metamorphism.

Much of the ground is, in reality, already covered in greater detail in Boeke-Eitel, *Grundlagen der physikalisch-chemischen Petrographie* (1923), but the book will be useful to students principally for the extensive references to the recent literature of the subject.

Inspection will reveal that in some departments of the subject the literature is not quite up to date, but doubtless this is to be ascribed to the difficulty of access to world literature in Germany since 1914 rather than to lack of industry on the part of the author.

In the same series two further volumes on related subjects are promised, and are now in preparation: (*a*) Fortschritte der physikalischen Kristallographie, by E. Schiebold; (*b*) Entwicklung der speziellen physikalisch-chemischen Petrographie, by K. Spangenberg.

C. E. T.

Cambrian Geology and Palaeontology, V, No. 3, Cambrian and Ozarkian Trilobites. By C. D. Walcott. Smithsonian Misc. Coll., vol. lxxv, No. 3. pp. 61–146, with 10 plates. 1925.

WE welcome another part of Dr. Walcott's important contributions to the study of the Lower Palaeozoic Trilobites of North America. The present number is of especial interest, as it contains many descriptions and figures of Ozarkian Trilobites, which will no doubt aid in determining the position of the Ozarkian rocks in the Lower Palaeozoic sequence.

It seems clear that we must look to North America for the origin of the trilobite-fauna which characterizes the Ordovician strata of Europe.

REPORTS AND PROCEEDINGS.

Mineralogical Society.

3rd November, 1925.

C. S. Garnett: The Dissociation of Dolomite. Further evidence is put forward in support of conclusions adduced in a previous paper that true dolomite dissociates under the influence of heat in a single step and not in two stages as formerly supposed. The setting of semi-burnt dolomite with water is due to free lime and not to a mixture of magnesium oxide and calcium carbonate.

B. J. Tully: A new Refractometer. The special features of this new refractometer are thorough rigidity and an exceptionally large and flat field of vision due to the long optical system employed, the shadow edges being straight instead of curved as in older types. All adjustments for focussing, lighting, etc., being independent of the main body, which contains the optical system and graticule

scale in a dust-proof enclosure, little damage is possible by inexperienced usage.

A. Russell: Notes on some new British localities for Barytocalcite and Alstonite. The occurrence of barytocalcite at the following new localities is described: Ayleburn Mine, Northumberland, two miles north of Alston, where it occurs, abundantly and well crystallized, with blende in brown limestone; Heartycleugh Mine, West Allendale, Northumberland, in small quantity with barytes; and Lolly Scar Mine, Nidderdale, Yorkshire, massive and in small crystals with fluor, chalcopyrite, witherite, etc. Alstonite, massive and in crystals of the usual habit, was found as a single specimen in the witherite vein worked in Ushaw Moor Colliery, near Durham.

Dr. G. T. Prior: The meteoric iron of Vaalbult and meteoric stones of Witklip and Queen's Mercy, South Africa. A mass of meteoric iron weighing 26 lb. was found on Vaalbult farm, Prieska Division, Cape Province. It is a coarse octahedrite having a percentage of nickel of about 7, with a ratio of iron to nickel of about 13. The Witklip stone fell on 26th May, 1918, on the farm Witklip in Carolina district, Transvaal, after a loud explosion and a flash of light. It is a grey chondrite resembling Cronstad. Only a few grams appear to have been preserved. The Queen's Mercy stone is also a grey chondrite which fell on 30th April, 1925, about twenty miles from Matatiele, Cape Province, after appearance of a bright light and a loud detonation. The stone, which measured about $1\frac{1}{2}$ foot in length, was broken up by the natives and only a few fragments have been recovered.

CORRESPONDENCE.

THE BASE OF THE "MILLSTONE GRIT" NEAR HAVERFORDWEST.

Sir,—In view of the interest which has been aroused in the problems of the Millstone Grit by the recent publication of Mr. W. S. Bisat's paper on the Carboniferous Goniatites of the North of England and their Zones, it may be useful to put on record some further evidence bearing upon the relation of the Millstone Grit to the Carboniferous limestone near Haverfordwest.

The section in the old quarry near Haroldston St. Issels, which shows the base of the grit resting with a marked unconformity on the *Seminula* zone, is described in the Survey Memoir on the Haverfordwest district (p. 151), and reference is made to a black shale band, crowded with goniatites, which occurs in the Millstone Grit some 10 to 15 feet above the base of the lowest quartzite band. When these goniatites were originally collected they were reported to be *Glyphioceras bilingue* and no particular significance was attached to them. Last Easter I visited the section again in order to obtain a fresh collection of these fossils, a part of which was submitted to Mr. Bisat for his opinion. He identifies

them with *Reticuloceras reticulatum* mut. β, a fossil which is characteristic of an horizon near the Third Grit in Lancashire. This identification agrees specifically with the original identification by the Survey palaeontologists. Any doubt there may be regarding the significance of the break between the Millstone Grit and the Carboniferous limestone is set at rest by the relations of the two formations at this locality. The fossils obtained from the limestone indicate, it is believed, the lower part of the *Seminula* zone (S1) and the rest of the Main Limestone, which attains a thickness of about 600 feet at Pendine, some miles to the east and a much greater thickness farther south, is missing owing to overstep at the base of the Millstone Grit. The horizon of the above-named goniatite in Lancashire is several thousands of feet above the base of the Upper Carboniferous (Lancastrian of Bisat). In the Haverfordwest Memoir (p. 151) the suggestion is made that there is overlap at the base of the grit since the shale bands near Haverfordwest appear to correspond with bands that are underlain farther east by a considerable thickness of shales and quartzites that are not represented in the western area. Definite evidence in support of this suggestion can only be obtained by the collection of fossils from the shales in the Eastern districts.

O. T. Jones.

The University,
Manchester.

THE TECTONICS OF THE SOUTHERN MIDLANDS.

Sir,—I have read with much interest the paper on the "Structure of the Southern Midlands," appearing in your July issue. Attention is there drawn to a probable axis of unrest running south-eastwards from Nuneaton which, it is suggested, may account for the sudden disappearance of the Lower Greensand at Leighton Buzzard. I write to call attention to further evidence bearing on the existence of this axis. The line indicated above, if continued to the south-east, enters the Tertiary outcrop in north-west Middlesex, in the Pinner-Watford area. It is a significant fact that the Reading Beds are exceptionally thin and sandy in this region, while they thicken both north-eastwards and south-westwards, resuming at the same time their normal lithology. Nearer London there is evidence that the same axis was active in Thanetian times, for the Thanet Sands are thin and locally absent over a limited tract in north-west London. It is also of interest to note that the London Clay thins westward against this axis, but thickens again on the further side towards the Bagshot country. The full evidence for these statements cannot be given here, but it is hoped that it will soon be published.

It may be thought by some a far cry from London or Watford to Nuneaton, but there can be no doubt that posthumous movements along several Charnian lines materially affected Eocene sedimentation. One need only refer to the case of the Ipswich axis so fully worked

out by Professor Boswell. Further, when it is remembered that the Palaeozoic floor is at comparatively small depth beneath the London Basin, it seems natural, if not inevitable, that the thin Neozoic cover should accommodate itself in detail to the structure of the thicker and more rigid underlying mass.

S. W. WOOLDRIDGE.

ANNOUNCEMENTS AND INQUIRIES.

The late Professor Charles Lapworth and Dr. T. Stacey Wilson were engaged for many years in mapping, on the 6-inch and 25-inch scales, the Cambrian rocks of the Harlech dome. Their work was unfinished at the time of Professor Lapworth's death, and Dr. Wilson finds that he has not sufficient leisure to complete the work himself. In these circumstances Professor W. S. Boulton, who has the custody of Professor Lapworth's field-maps, has, with Dr. Stacey Wilson's approval, invited Dr. C. A. Matley, a former student of Professor Lapworth, to continue the survey of the area and to put the results into a form suitable for publication. Dr. Matley has consented to do this, and will take up the work next summer after completion of his own work in South-Western Lleyn.

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